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# A NEW METHOD FOR SATELLITE ORBIT DETERMINATION USING AN OPERATIONAL WORLDWIDE TRANSPONDER NETWORK

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— GODDARD SPACE FLIGHT CENTER —  
GREENBELT, MARYLAND

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USING AN OPERATIONAL WORLDWIDE TRANSPONDER NETWORK

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ABSTRACT

A New Method for Satellite Orbit Determination Using an Operational Worldwide Transponder Network. This new method utilizes computer programs developed for the forthcoming ATS-F/NIMBUS-F Tracking and Data Relay Experiment where the basic tracking measurements are multiple path round-trip propagation times and rates. This method of orbit computation has recently been successfully evaluated by tracking a geostationary satellite (ATS-3) using an existing VHF (150 MHz) network of automatic transponders. A master station sequentially interrogates each transponder via the ATS-3. The master site is located at Schenectady, N. Y. and four automatic transponders were located at Shannon, Reykjavik, Buenos Aires, and Seattle respectively. Data at hourly intervals were collected during a 24 hour period on April 18-19, 1973. After correcting this data for known systematic errors it was provided as input to an orbit determination program (GSFC-Navigation Analysis Program) where all satellite motions during signal propagation are rigorously accounted for. The resulting estimated ATS-3 orbit yielded observational residuals on the order of 100 meters. By using more than one satellite the present scheme is further capable of accurately locating several stationary or mobile terminals as part of the overall orbital solution.

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# A NEW METHOD FOR SATELLITE ORBIT DETERMINATION USING AN OPERATIONAL WORLDWIDE TRANSPONDER NETWORK

## INTRODUCTION

For the past five years the NASA geostationary Application Technology Satellites (ATS-1, ATS-3 and ATS-5) have been used in a series of ranging experiments to locate remote transponders placed at fixed locations as well as on ships, aircraft and buoys. These experiments have been carried out using the General Electric Optical Observatory ranging system with the master station located at Schenectady, N. Y. (Reference 1) and using NASA predictions of satellite positions.

During April 18-19, 1973 a tracking test was conducted to determine to what extent the ATS-3 orbit could be recovered directly using a number of remote transponders interrogated by the Schenectady master station. The primary purpose of this test was to evaluate software which will be used in conjunction with the forthcoming ATS-F/NIMBUS-F tracking and Data Relay experiment. However, the technique also affords the possibility of periodically accurately calibrating remote transponders by solving for time delay biases along with the satellite state vector. Trilateration could then be used with multiple satellites to afford quick and accurate position fixes on Earth based transponders. Such calibration of remote sites via orbit computation is for example currently being performed by NASA in the routine calibration of the MINITRACK interferometer tracking system.

The feasibility of determining such geostationary orbits using ranging data from a master station to a worldwide network of transponders has been demonstrated using ATS-3. The orbit computation described herein used the data from the G. E. VHF (nominal 140 MHz) system which has the deployment of transponders indicated in Figure 1. The G. E. L-Band (nominal 1600 MHz) system is also available for similar experiments using ATS-5 and future orbit determination experiments with this data type are planned.

Since the measurement via ATS-3 were made at VHF, corrections for ionospheric ranging bias were quite important. For this purpose the recently implemented NASA-GSFC Ionospheric Correction Model (Reference 2) was applied to all data.

The computer programming required for processing this special range sum data type was developed for the ATS-F/NIMBUS-F and the ATS-F/GEOS-C satellite-to-satellite tracking and orbit computation experiments scheduled for mid 1974. These latter experiments have as one primary objective the probing of the geopotential field (Reference 3).

Location	Latitude	Longitude	Height Above Sea Level (meters)	Nominal Transponder Delay (microseconds)
*Shannon, Ireland	52° 46' 55"N	08° 55' 50"W	9	432255.1
*Buenos Aires, Argentina	34° 35' 03"S	58° 22' 16"W	48	432114.0
*Reykjavik, Iceland	64° 07' 47"N	21° 56' 12"W	30	432285.4
*Seattle, Washington	47° 24' 00"N	122° 09' 30"W	165	432251.9
Schenectady, New York	42° 50' 53"N	74° 04' 15"W	404	439469.6

\*Transponders used in ATS-3 Orbit Computation

Figure 1. Transponder Locations and Nominal Time Delays

### Tracking System Description

The overall tracking system configuration used during the April 18-19, 1973 24 hour observation of transponders via ATS-3 is shown in Figure 2. As shown in Figure 3, the "geostationary satellite" although at synchronous altitude undergoes a sinusoidal slant range change of  $\pm 350$  km as observed from the Schenectady tracking site. This is due to the nominal 3° orbital inclination and Figure 3 merely emphasizes the fact that trilateration must necessarily include the change

### OVERALL TRACKING SCHEME

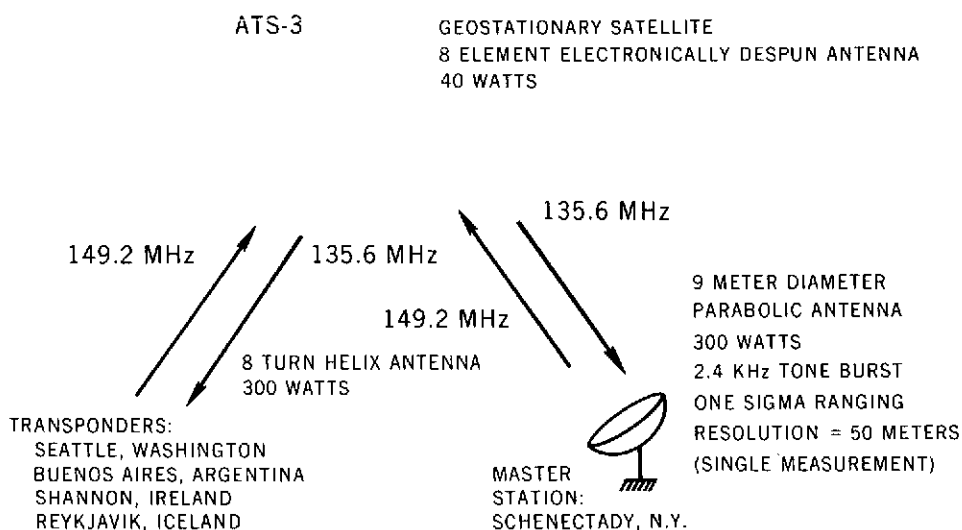


Figure 2. Overall Tracking Scheme

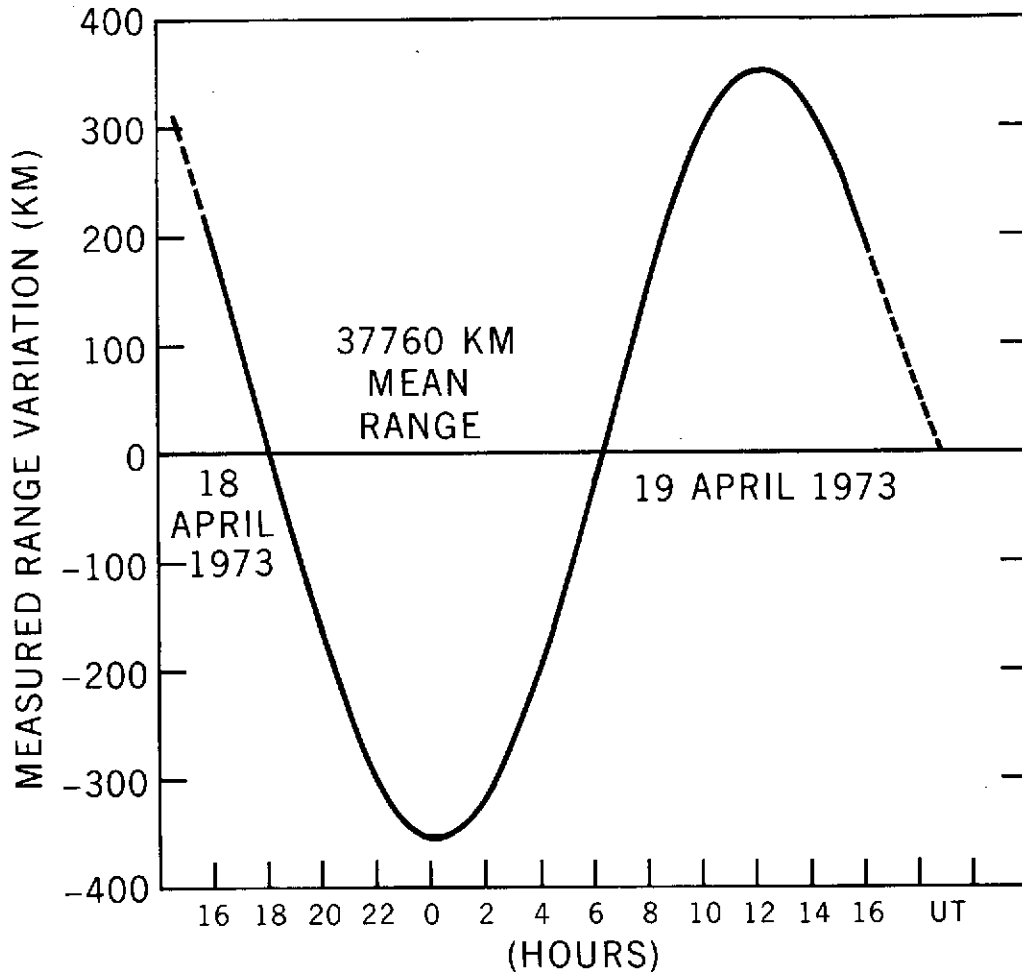


Figure 3. Direct Ranging Measurement (Schenectady, N.Y. to ATS-3)

in synchronous satellite position with time. The range-rate associated with Figure 3 is similarly periodic with a peak amplitude of 25 meters per second.

General Electric's Radio-Optical Observatory near Schenectady, New York is the master station for the measurements. Ranging interrogation originate there, time interval measurements are made, data recorded and a time-shared computer is used for data processing and formatting. Automatic VHF transponders located geographically at Buenos Aires, Shannon, Seattle, and Reykjavik were interrogated over a 24 hour period via ATS-3 according to the tracking schedule indicated in Figure 4. A diagram of the basic transponder is shown in Figure 5. Direct ranging from Schenectady to ATS-3 was similarly used in the orbit determination process.

SCHENECTADY

RANGE TO ATS-3 EVERY 2 SECONDS

SHANNON

BUENOS AIRES

REYKJAVIK

SEATTLE

}

ONE COMPLETE INTERROGATION  
EVERY 12 SECONDS

10 MINUTES OF TRACKING DATA PER HOUR FROM  
16:20 UT 18 APRIL 1973 TO 16:20 UT 19 APRIL 1973

APPROXIMATELY 12500 MEASUREMENTS COMPRESSED  
TO 125 OBSERVATIONS USING POLYNOMIAL SMOOTHING  
PRIOR TO ORBIT COMPUTATION

Figure 4. Sequential Ranging Schedule

The VHF experiments are conducted with a range tone frequency of 2.4414 kHz. The ranging code is frequency modulated on a carrier frequency of 149.22 MHz with an RF bandwidth of 15 kHz. The signal is relayed down from the satellite at 135.6 MHz. The transponder receives the tone cycles via the geostationary satellite. All of the tone cycles received from the satellite, even though they may be interrogations for other transponders, are applied to a phase matching circuit. Ten nanosecond clock pulses are produced at the times of the zero crossings of the received tone. A local clock controlled by a crystal oscillator generates clock pulses at the same rate as the zero crossings of the tone. A digital phase matcher shifts the phase of the locally generated clock pulses so that they are coincident with the received clock phase. The digital phase matcher accomplishes an initial phase match to within a few microseconds in one clock period. It then averages the remaining phase difference over 256 clock periods, and then refines the phase setting to within  $0.1 \mu\text{s}$  of the received data clock. The averaging process smooths "jitter" due to noise and improves the timing precision by the square root of the number of cycles averaged. The local clock continues to generate pulses in the same phase after the end of the received ranging code preamble.

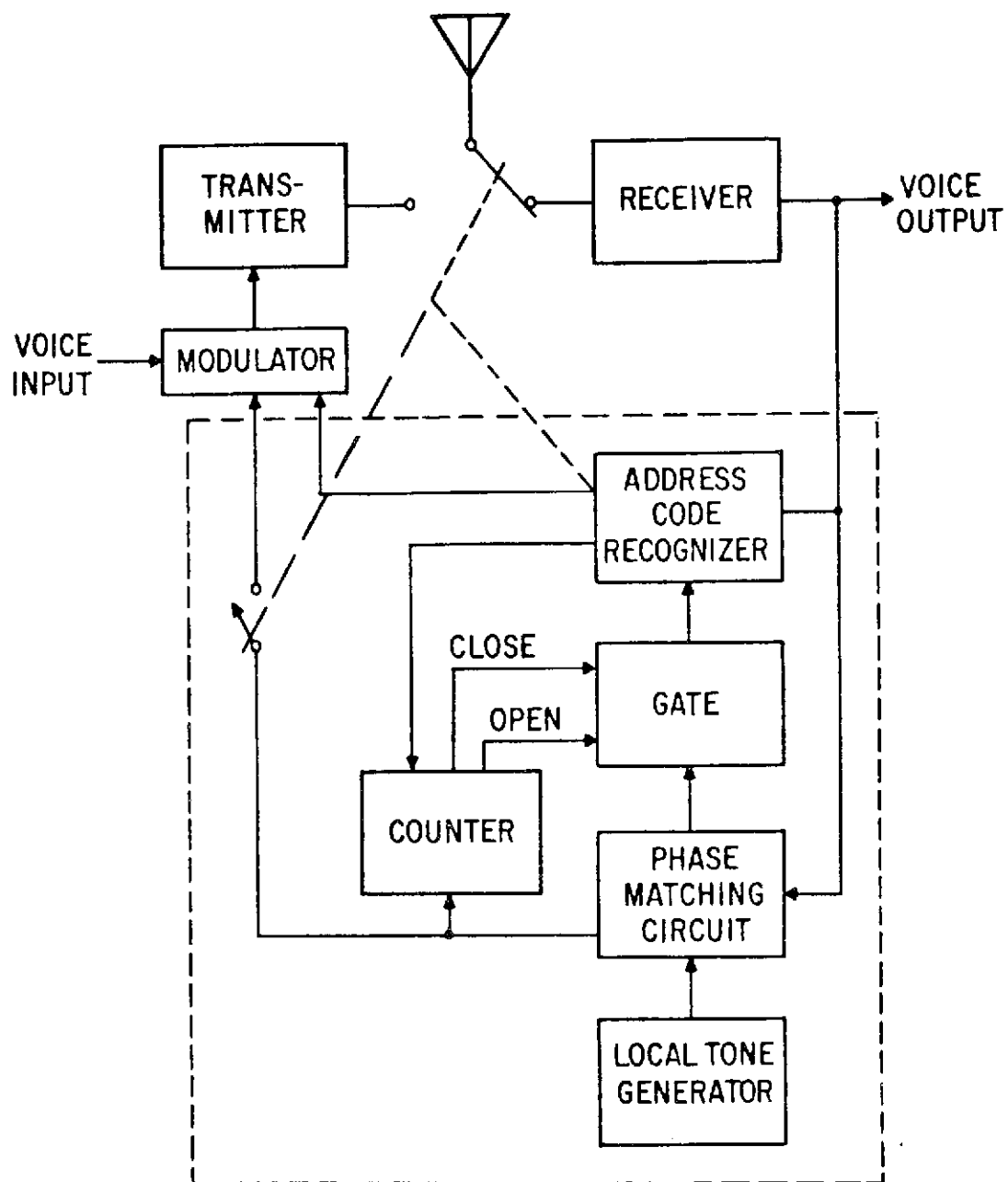


Figure 5. Basic Tone-Code Transponder

The ranging code is applied to the address code correlator which is a shift register and summing circuit prewired for the individual address code of the transponder. As the received address code is clocked into the correlator the summing circuit output is low unless the address code is exactly centered in the correlator and matches the prewired code. When the correlation occurs, the correlator output is high for the period of one tone or data clock cycle. While the correlator output is high it opens a gate and the one data clock pulse that occurs during that period is gated out of the phase matcher-correlator. The phase of the gate is shifted by a specific amount so that the properly phased clock pulse is approximately centered in the open gate. The one clock pulse that is gated out during the correlation pulse is a precise and completely unambiguous measure of the time the ranging code was received from the satellite. The clock pulse causes the antenna to switch from the receiver to the transmitter, turns on the transmitter if it is not already on for duplex operation, and causes the transmission of the preamble code. The code is clocked from the locally generated clock. A counter measures the exact number of clock pulses in the preamble code and then initiates transmission of the address code. At the end of the address code the transponder is switched back to the receive mode.

When the Radio-Optical Observatory receives the vehicle response as relayed through the satellite it performs an identical phase matching-correlation process to make an unambiguous measurement of the time of reception and to check the address of the returned signal. An automatic sequencer and a digital clock initiate interrogations at regular intervals such as once each two seconds and data are automatically recorded on punched tape and on a teletypewriter, each line of data containing the time interval for the signal to go from the Observatory to the interrogating satellite and return, the identification number of the vehicle that was interrogated, the time in hours, minutes and seconds of the interrogation, and the time intervals associated with the transmission of each interrogation to the sequential scanned transponders.

It is these basic time delay measurements which were corrected for ionospheric effects and then used by the NASA Navigation Analysis Program for purposes of orbit computation.

## IONOSPHERIC CORRECTIONS

The Earth's ionosphere introduces systematic perturbations to all radio tracking data. At present NASA radio tracking is conducted in the approximate frequency range of 140 MHz to 6 GHz. At the lower frequencies daytime ionospheric biases can easily reach several kilometers in range, several meters per second in range rate, and up to two or three milliradians in angle. At the higher frequencies these values decrease as the inverse square of frequency. However, in all cases

this ionospheric bias is greater than the basic tracking system resolutions involved. The lower tracking frequencies are preferred from the standpoint of simplified antenna pointing and hence ease of signal acquisition. The higher frequencies are preferred from the standpoint of high telemetry data rates and extremely precise orbit computation such as associated with satellite geodesy.

The VHF tracking data was corrected using the highly successful ionospheric correction model (Reference 2) incorporated into the recently completed Goddard Trajectory Analysis Program which eventually will provide operational support for all GSFC missions. The overall correction scheme is shown in Figure 6. These corrections are a function of predicted solar activity, tracking station latitude and longitude, universal time and station to spacecraft and transponder geometry.

The mathematically closed form ionospheric profile is shown in Figure 7. It consists of segments of parabolic, parabolic-squared and exponential functions. The functions are matched in magnitude and slope at each boundary. The maximum electron density,  $N_m$ , is directly related to the  $f_oF_2$  critical frequency. This density is on the order of  $10^{11}$  to  $10^{12}$  electrons per meter<sup>3</sup> depending on time of year, time of day, solar activity, geographic latitude and longitude and so on. The corresponding vertical total integrated electron content varies from  $10^{16}$  to  $10^{18}$  electrons per meter<sup>2</sup>. Also the height of the maximum density,  $h_m$ , is a function of the scalar factor  $M(3000)F_2$  and will typically range from 200 to 400 km. The parameters affecting profile shape (e.g.  $K_1$ ,  $K_2$ ,  $K_3$ ,  $Y_m$ ,  $Y_e$ ) were empirically derived from the large data base indicated in Figure 8 and are stored in the computer in the form of look up values which are functions of latitude, longitude,  $f_oF_2$  and time of year.

The time delay (or "range") corrections applied to the ranging data were calculated using NASA's best estimate of worldwide maximum electron density distribution in conjunction with the foregoing ionospheric correction model. An example of total one-way path delay is given in Figure 9 which pertains to the Schenectady, ATS-3, Seattle path during April 18-19, 1973.

#### Data Processing and Orbit Computation

A generalized block diagram depicting the data processing functions is given in Figure 10. The raw data collected by the G. E. tracking system previously described consisted of the two way signal propagation delays between the master site (Schenectady), the ATS-3, and four remote ground transponders. The two-way signal propagation delay between the master site and the ATS-3 is essentially equivalent to a range measurement. Similarly, the observed delay over the two-way path from master site, to ATS-3, to remote transponder is equivalent to an

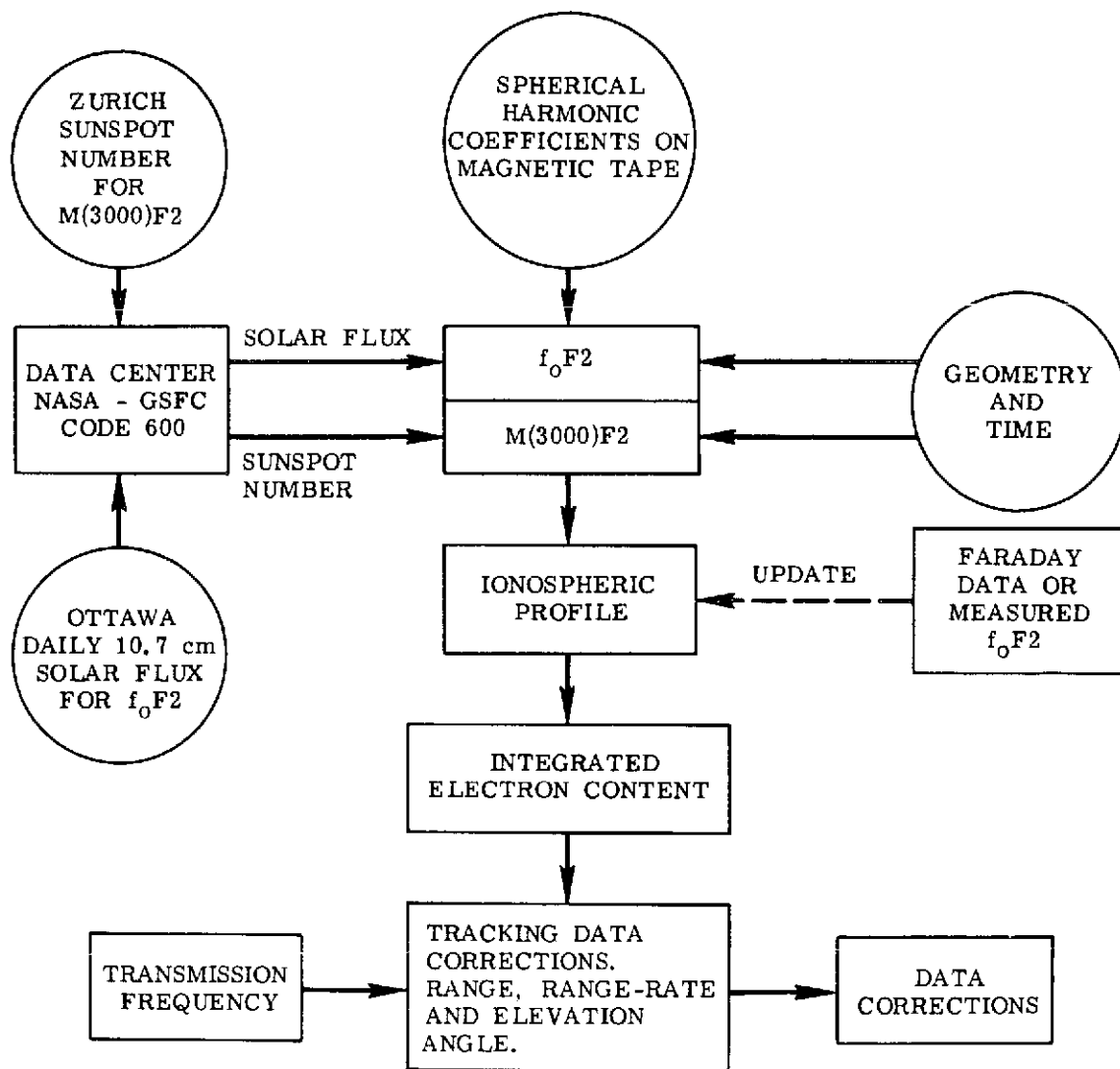


Figure 6. NASA-GSFC Ionosphere Model Implementation

observation consisting of the sum of ranges, master site to ATS-3 and ATS-3 to remote transponder. Though the reduction programs accept and operate on the tracking observations given in the form of time delays, we will for the sake of convenience treat them here in terms of equivalent ranging observations.

The data utilized in the present experiment extended over a 24 hour period during the 18th and 19th of April 1973. During each of the 24 hours approximately 10 minutes of continuous tracking was achieved, resulting in the collection of 125000 observations. Referring to Figure 10, these observations were processed

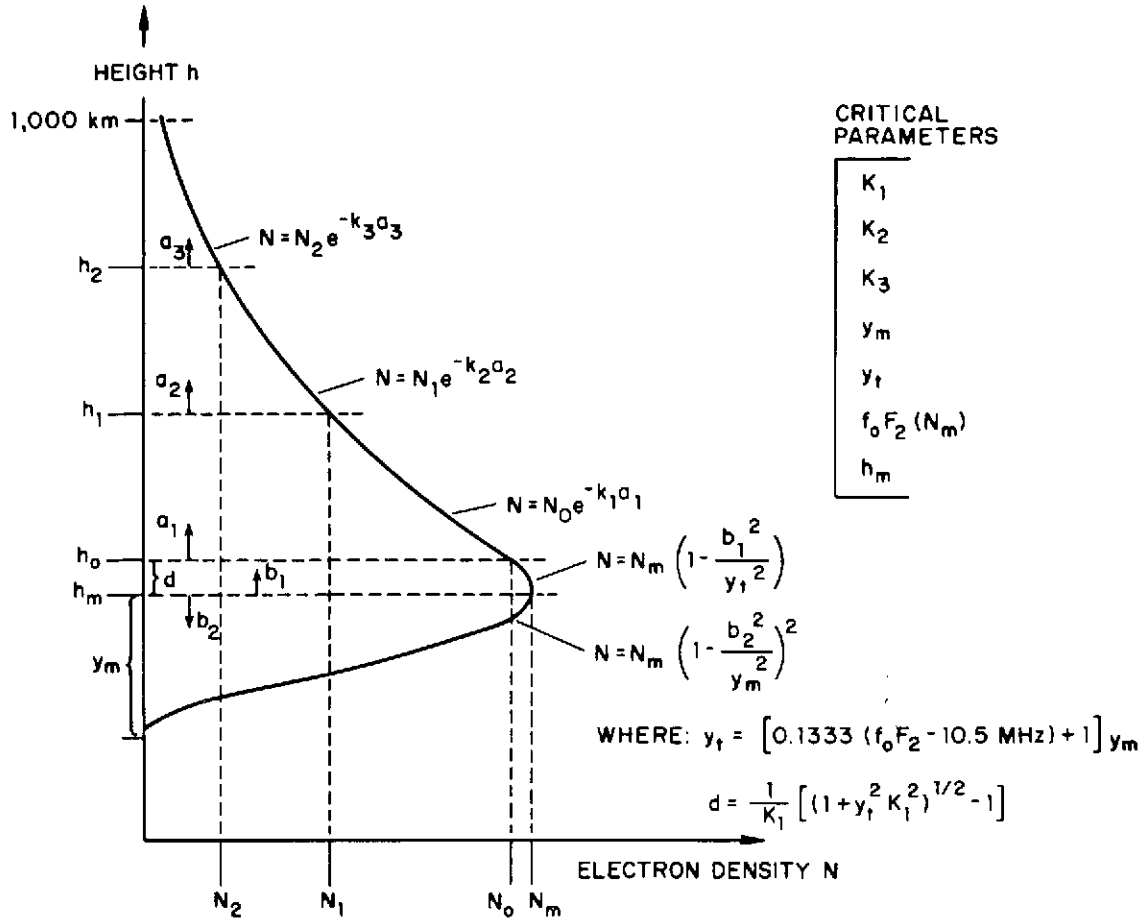


Figure 7. Composite Profile

with the aid of polynomial smoothing algorithms resulting in the further compression of the raw data to an equivalent set of only 125 observations (or one observation/hour from each site). Our purpose here was to edit the data for any wild points and reduce the time required for subsequent orbit computations. This compacted subset of the tracking data was then further modified through the application of ionospheric refraction corrections obtained by means of the GSFC model previously described, and through the addition of nominal transponder delays. Typical values of ionospheric corrections and nominal transponder delays are given in Figures 9 and 1 respectively.

ATS-3 orbit estimates from the above data were obtained with the aid of the NASA/GSFC Navigation Analysis Program (Reference 4). This is a generalized least squares parameter estimation program designed to accept and process numerous types of tracking observations, and includes algorithms for rigorous treatment of single or multi-satellite time delay measurements. The program

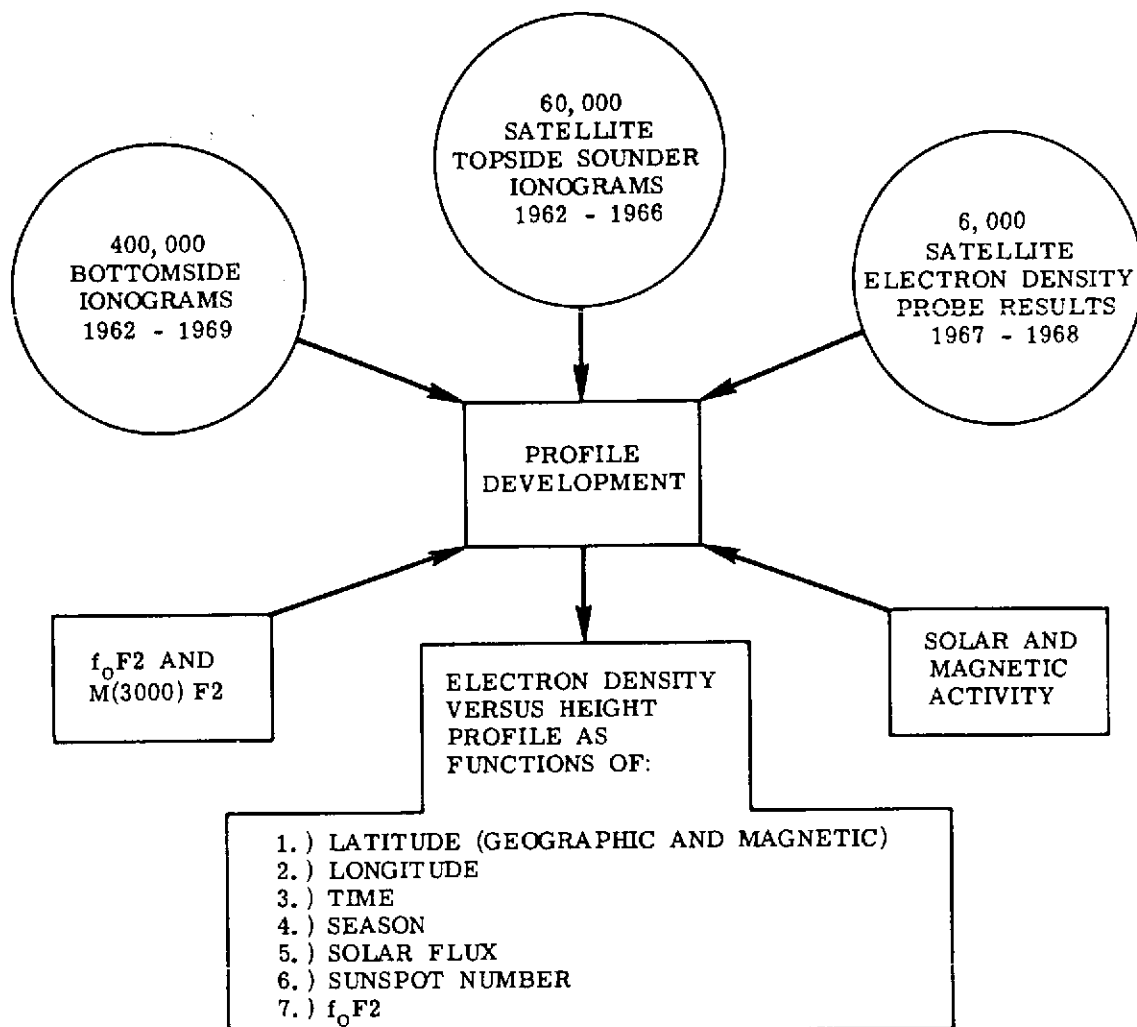


Figure 8. NASA-GSFC Ionosphere Model Development

user must provide only a rough estimate of the orbit to be estimated, and may select or input a gravity field model. In the present exercise we have selected the built-in gravity model for the earth (Goddard Earth Model No. 2) which is given in terms of spherical harmonics to order, degree 22. Lunar and solar perturbations are provided by means of the JPL ephemeris residing on permanent disk file at the NASA/GSFC 360/95 computer facility.

Program output included the estimated ATS-3 orbit in the form of a state vector at the chosen epoch, estimates of instrumentation biases, standard deviations of these estimated parameters, their correlation matrix, and a listing of the resulting observational residuals from each signal path.

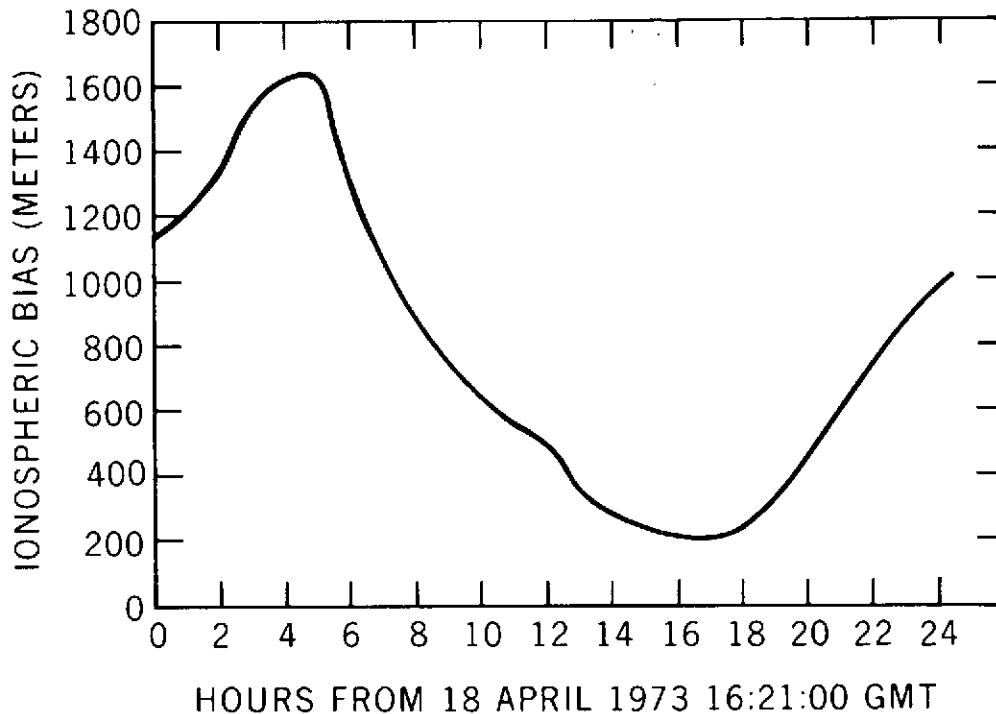
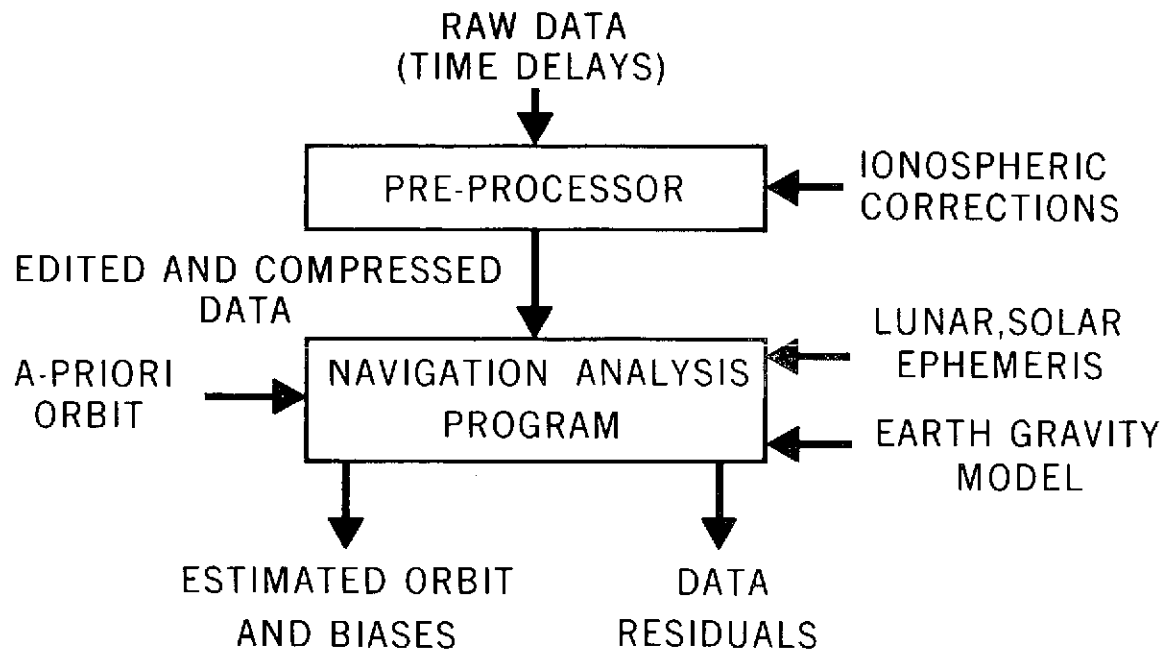


Figure 9. Ionospheric Delay Correction (Schenectady, ATS-3, Seattle Path)

### Summary of Results

A summary of the ATS-3 orbital estimates is presented in Tables A and B. These results are based on a simultaneous solution of eleven parameters comprising of the six parameters which define the satellite state vector at the chosen epoch, plus five parameters associated with measurement biases. The listed uncertainties are based on our a-priori estimates of data quality which were found to be consistent with the computed orbit observation residuals. Typical observation residuals for the master station (Schenectady) and a remote site are given in Figures 13 and 12 respectively. It should be noted that the residual RMS values of 104 and 80 meters respectively are consistent with our a-priori choice of data weighting. Residuals associated with the other remote transponders follow the same general pattern with RMS values on the order of 100 to 200 meters. From the results listed in Table A it is apparent that a high degree of correlation exists between X and Y coordinates of the estimated ATS-3 orbit. This is caused by the poorer observability relative to these parameters and is essentially indicative that our data does not yield statistically independent estimates of satellite position and velocities in its orbital (equatorial) plane. This is also evident from the high correlation between the recovered Keplerian elements  $\omega$  and  $M$  as given in Table B.



ATS-3 COMPUTED POSITION 19 APRIL 1973 0000 HRS UT

LATITUDE	LONGITUDE	INCLINATION
3.098°	291.588°	3.403°

Figure 10. Data Processing

As a further check on these results we repeated the previous reduction except that only half the data was utilized for orbit determination. In particular a new orbital estimate was obtained based only on the first half (12 hours) of the data. This orbit was then utilized to predict a set of computed observations for the entire span of 24 hours. The differences between the predicted observations and the actual observations were computed. The resulting differences between the predicted and actual observations for the data not utilized in our orbit computations was on the order of only 200 meters and demonstrated the general trend depicted in Figures 12 and 13. This tends to confirm our confidence in the estimated ATS-3 orbit and provides an independent accuracy check which is consistent with the overall tracking data quality.

We were also interested to determine the effects of our selected gravity model on these results. As can be expected, because of the high satellite orbit, a simple earth gravity model neglecting spherical harmonics above order 4 yielded essentially identical results. On the other hand when we removed the Lunar

Table A  
Recovered ATS-3 Orbit and Uncertainties in Cartesian Coordinates  
Epoch 4-19-73 O-H GMT

Inertial True of Date Coordinates				Sigmas		
X    -31487.190 km				26.5 km		
Y    27813.505 km				30.0 km		
Z    2271.127 km				0.3 km		
$\dot{X}$ -2.039 km/sec				0.002 km/sec		
$\dot{Y}$ -2.308 km/sec				0.002 km/sec		
$\dot{Z}$ 0.076 km/sec				2 cm/sec		
Correlation Matrix						
	X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$
X	1.0					
Y	0.999986	1.0				
Z	0.186605	0.187478	1.0			
$\dot{X}$	-0.999998	-0.999993	-0.186271	1.0		
$\dot{Y}$	0.999989	0.999999	0.187738	-0.99995	1.0	
$\dot{Z}$	0.258282	0.257620	-0.000982	-0.258205	0.258132	1.0

Table B  
Recovered ATS-3 Orbit and Uncertainties in Keplerian Coordinates  
Epoch 4-19-73 0 Hours GMT

Keplerian Elements			Sigmas			
a	42163 km		104 meters			
e	0.00254		0.8E-6			
i	3.403°		0.4E-3 deg.			
Ω	73.1233°		0.6E-1 deg.			
ω	31.756°		0.28E-1 deg.			
M	33.538°		0.25E-1 deg.			
Correlation Matrix						
	a	e	i	Ω	ω	M
a	1.0					
e	-0.0868	1.0				
i	0.0764	-0.4232	1.0			
Ω	-0.2807	0.0213	-0.3127	1.0		
ω	-0.1262	-0.1533	-0.5704	0.6470	1.0	
M	0.1606	-0.0035	0.6502	-0.7056	-0.9768	1.0

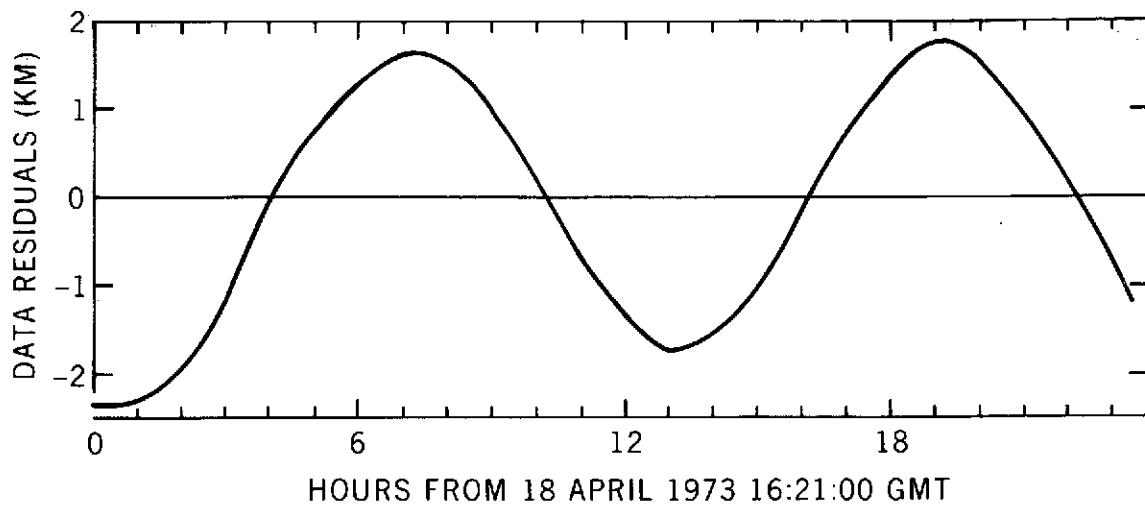
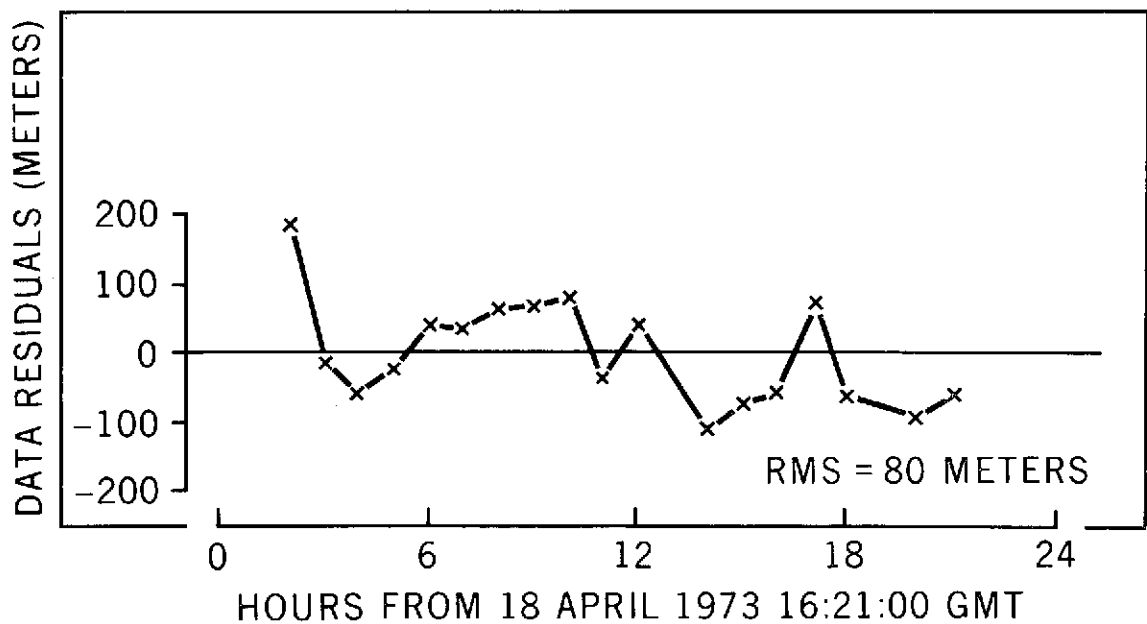
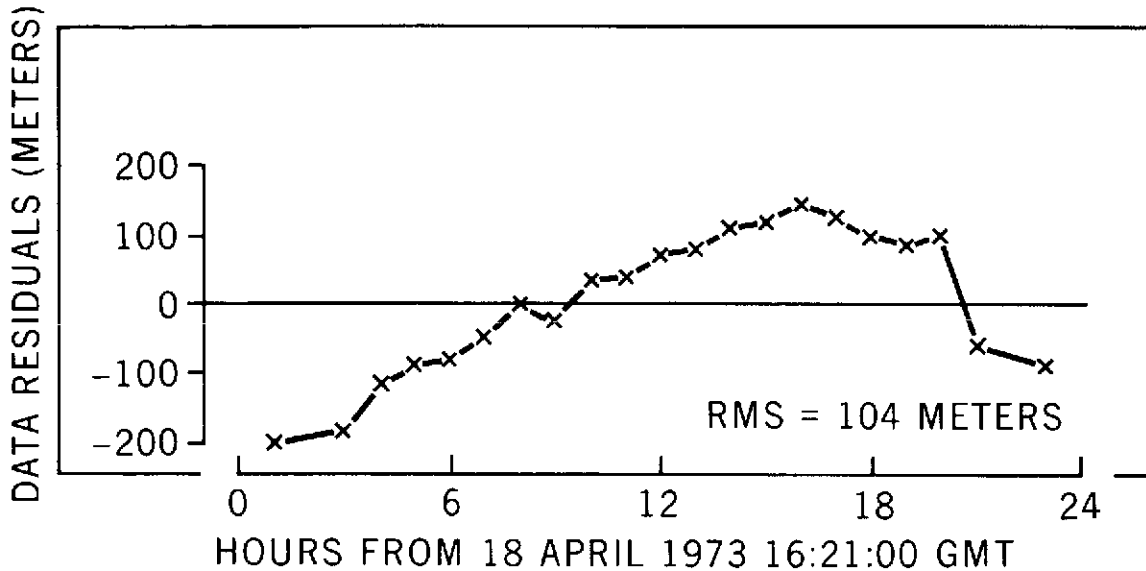


Figure 11. Shannon Range Sum Residuals if Lunar Gravity Not Included



NOTE: NOMINAL EQUIPMENT DELAY = 0.43 SECONDS  
 RECOVERED CORRECTION = 8 MICROSECONDS

Figure 12. Remote Transponder (Shannon, Ireland) Range Sum Residuals



NOTE: NOMINAL EQUIPMENT DELAY = 796 MICROSECONDS  
 RECOVERED CORRECTION = 10 MICROSECONDS

Figure 13. Master Station (Schenectady, N.Y.) Range Residuals

gravity perturbations from our model, the resulting orbit yielded observational residuals ranging to 2000 meters, as shown in Figure 11. The residuals are in this case periodic with a period of 12 hours due to Lunar perturbations on the ATS-3 synchronous orbit.

#### REFERENCES

1. Anderson, R. E., "Experimental Investigation of Aeronautical and Maritime Communications and Surveillance Using Satellites," International Astronautical Federation Congress Baku, USSR, October 13, 1973.
2. Schmid, P. E., R. B. Bent, S. K. Llewellyn, G. Nesterczuk and S. Rangaswamy, "NASA-GSFC Ionospheric Corrections to Satellite Tracking Data," NASA-GSFC, X-591-73-281, December 1973.
3. Lynn, J. J. and P. E. Schmid, "Detection of Gravity Anomalies from Satellite-to-Satellite Tracking Data," American Geophysical Union 53rd Annual Meeting, Washington, D.C., April 21, 1973.
4. Lynn, J. J., "Navigation Analysis Program, User's Guide," NASA/GSFC Contract NAS5-11915, Old Dominion Systems, Inc., April 1973.